Density as Estimator of Dimensional Stability Quantities of Brazilian Tropical Woods

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Wood is a material widely used in various sectors of construction, such as in structures and building components. The volume of wood extracted from tropical forests has reached a considerable amount, and this wood is marketed with popular names without prior characterization. Wood density is an easy property to measure, and its use as an estimator of other properties is very common in this sector. This study investigated the possibility of the estimation of important quantities in dimensional stability of Brazilian tropical woods by using the density at 12% moisture content, anhydrous density, and basic density. Testing the ability to estimate radial, axial, tangential, and volumetric shrinkage, anisotropy coefficient, coefficient of volumetric rate of volumetric shrinkage, as well as the rate of volumetric swelling using the densities above, with linear, exponential, geometric, and logarithmic models, the best determination coefficient was: R^2 = 19.58%. The results were, in summary, that the variable density was not a good estimator of the dimensional stability of the wood.

Keywords: Density; Dimensional; Stability; Physical properties; Dried lumber; Tropical wood

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INTRODUCTION

Wood is appreciated in building construction and many other industries. The required lumber production to meet demand makes this sector one of the leading employers and drives the economy in Brazil (Fiorelli and Dias 2003; Almeida *et al.* 2015; Christoforo *et al.* 2015). Wood is used either directly in the structure of the building or as a component of other subsystems (De Araujo *et al*. 2016). In environmental terms, wood is great for atmospheric carbon sequestration, because during photosynthesis atmospheric carbon dioxide is used to facilitate the tree formation (Hellmeister 1973; Calil *et al.* 2003; Carreira *et al.* 2012).

Wood from Brazilian rainforests has a high commercial value due to its physical, mechanical, and organoleptic properties. According to IMAFLORA (2003), at least 400,000 m^3 of tropical wood is extracted from forest management areas every year, which is approximately 15% of the total (adding unscreened volume).

Lumber extracted from tropical wood is largely used without characterization, yet it is marketed with popular names; therefore wood from many species is being misused due to the lack of measurement of its properties (Almeida *et al.* 2014; Molina *et al.* 2016). In this context, the characterization is prescribed by the standard document ABNT NBR 7190 (1997), conducted in specialized laboratories, and has favored the best application of these essences.

To facilitate the characterization procedures, it is common to adopt relationships between properties, using one of them (the more easily obtained) to estimate the other. Undoubtedly, apparent density (ratio between mass and volume of a specimen at known moisture content) is the more easily obtained property (Dias and Lahr 2004; Abruzzi *et al.* 2013; Sales and Lahr 2014).

With regard to wood dimensional stability, properties such as density, specific gravity, density at 0% moisture, moisture content, total shrinkage, saturation point of fibers, and coefficient of anisotropy are important parameters. Thus, the best use of the material also depends on these values (Usta and Guray 1998; Logsdon 1999; Boldin *et al.* 2008; Lubas *et al.* 2008; Quartaroli *et al.* 2010; Chowdhury *et al.* 2012; Moore *et al.* 2015; Kotlarewski *et al.* 2016).

Several authors have studied related themes, but not for tropical essences.

Kärki (2001) studied the variations of density and shrinkage of *Populus tremula*, quantifying them along the tree height and the distance between pith and bark. In these conditions the results could not be generalized.

Kord *et al.* (2010) evaluated the shrinkage parameters and related them to density for *Populus euroamericana*. Twenty-two-year-old trees were considered, and it was possible to conclude there is a slight trend to satisfactory correlation among the studied variables. The number of samples used in the research makes it impossible to generalize the results.

Sadegh *et al.* (2012) studied trees among the ages of forty-eight to fifty-two years. In the case of *Tamarix aphylla*, one of the main species from the dunes region (Iranian Desert), it was concluded that coefficients of determination are low when one tries to relate density with shrinkage percentages in the radial and tangential directions in wood.

Pliura *et al.* (2005) sought to determine some correlations between density and shrinkage percentages in the three main directions of wood in three clones: *Populus deltoides* × *P. nigra*, *P. trichocarpa* × *P. deltoids*, and *P. maximowiczii* × *P. balsamifer*. At ten years old, these trees came from regions that provided significant variations in their growth rate. The results obtained did not show dependence among these variables.

Sotelo Montes *et al.* (2007) examined the variation of physical properties of wood from young trees of *Calycophyllum spruceanum*, species from the Peruvian Amazon, widely used for various applications. In the age group considered, the correlation parameters did not reach consistent values to ensure the dependence between density and shrinkage percentages.

Leonardon *et al.* (2010) studied different anatomical and chemical factors of the wood and their influence on shrinkage in the main directions of wood, concluding that anatomical complexity, architecture of the constituent cells, and chemical composition of species can explain more precisely wood shrinkage than just the density of samples.

Considering the influence of heat treatment in pieces of *Araucaria angustifolia*, Oliveira *et al.* (2010) concluded that the sapwood showed better dimensional stability when heated compared to the heartwood, at temperatures ranging from 120 °C to 200 °C. The point noted by authors could not be extrapolated to tropical dicotyledons.

Schulgasser and Witstum (2015) confirmed that the rate between density and volumetric shrinkage, such as adopted by Kollmann and Côté (1968), does not consider topics related to the anatomic complexity of essences. Based on a mechanical analysis of a cell model, wherein the implications of the wall microstructure are taken into account, the authors show that the nature of its microstructure is crucial for explaining the shrinkage behavior of wood, with respect to its density.

Abruzzi *et al.* (2013) tried to relate density and anatomical characters for poles installed in the electrical network, of three *Eucalyptus* wood species. Image analysis showed that the mean lumen diameter of fibers varied expressively among the three species studied, in line with the wood density obtained in a laboratory, for poles with several years in service, as well as for unused poles. No references to poles of other species were used in the paper.

Zeidler (2013), researched the quality of wood (*Corylus colurna*) originating in Turkey and introduced in the Czech Republic, and recorded, among other things, that the shrinkage of Turkish hazel wood was minimally correlated with the wood density.

In an attempt to facilitate the characterization of Brazilian tropical woods available for sale, as well as to provide subsidies to their best use as building components and in the furniture industry, it is necessary to investigate the possibility of estimation of dimensional stability parameters cited using density as reference. In literature, papers by Dias and Lahr (2004), Hernández (2007), Zeidler (2013), Almeida (2015), Simsek and Baysal (2015) and Almeida *et al*. (2017) can be regarded as references, although not conclusive on the subject.

Therefore, in this context, the present study aims to evaluate, for Brazilian tropical wood species, the possibility of estimating basic density, density at 0% moisture content, shrinkage in axial, radial, tangential directions, anisotropy coefficient, rate of volumetric shrinkage, and rate of volumetric swelling from density at 12% moisture content, through the study of correlation between these parameters. It is fitting to emphasize that the approach to these wood species is not a theme found widespread in the literature, attesting to the originality of this work.

EXPERIMENTAL

Materials

The density at 12% moisture content (ρ_{12}), density at 0% moisture content or anhydrous density (ρ_s), basic density (ρ_{bas}), radial (β_r), tangential (β_t), axial (β_l), and volumetric shrinkage (β_v), fiber saturation point (FSP), anisotropy coefficient (AC), coefficient of volumetric rate of volumetric shrinkage (β_v/PSF), as well as the rate of volumetric swelling (α_v/PSF) for Brazilian tropical essences studied were obtained based on to the recommendations of items B5, B6, and B7 from Annex B "Determination of the wood properties for structural design," NBR7190 (1997). They were made for each listed wood species, 12 specimens, totaling 180 samples and 1,980 determinations (11 properties for each sample), as already adopted by Dias and Lahr (2004).

The species used in this study are listed in Table 1. The sampling was based on strength classes or classes of resistances (CR) with three species for each class, according to NBR7190 (1997), to obtain representative results, given the existing wide range of densities, as it has been emphasized by several authors, such as Almeida *et al.* (2016).

Table 1. Brazilian Tropical Wood Species Used in this Study

Brazilian Popular Name	Scientific Name	Origin in Brazil (City/State)	CR	$\rho_{12,m}$ (kg/m³)
Cedro-doce	*Pachira quinata*	Bonfim do Sul/Roraima	C20	650
Cedro-amargo	*Cedrela* sp.	Caracaraí/Roraima		
Cambará	*Erisma* sp.	Cláudia/Mato Grosso		
Canafístula	*Cassia ferruginea*	Naviraí/Mato Grosso do Sul	C30	800
Catanudo	*Calophyllum* sp.	Vera/Mato Grosso		
Casca grossa	*Ocotea odorifera*	Bonfim do Sul/Roraima		
Angelim araroba	*Vataieropsis araroba*	Caracaraí/Roraima	C40	950
Cupiúba	*Goupia glabra*	Alta Floresta/Mato Grosso		
Angelim amargoso	*Vatairea fusca*	Caracaraí/Roraima		
Mandioqueira	*Qualea albiflora*	Bonfim do Sul/Roraima	C50	975
Castelo	*Gossypiospermun praecox*	Cláudia/Mato Grosso		
Tatajuba	*Bagassa guianensis*	Juína/Mato Grosso		
Angelim vermelho	*Dinizia excelsa*	Juína/Mato Grosso	C60	1000
Champanhe	*Dipteryx* sp.	Cláudia/Mato Grosso		
Itaúba	*Mezilaurus itauba*	Vera/Mato Grosso		

Methods

Based on Almeida *et al.* (2016), the regression models used to estimate the properties through the density at 12% moisture content (ρ_{12}), anhydrous density (ρ_s), and basic density (ρ_{bas}) are shown in Eqs. 1 through 4, where X is the independent variable (ρ_{bas}, ρ_{12}, ρ_s), Y the dependent variable (ρ_{bas}, ρ_s, β_r, β_t, β_l, β_v, AC, α_v/PSF, β_v/PSF), and "*a*" and "*b*" are two parameters of the adjusted functions (Eqs. 1, 2, 3, and 4), by the least squares method. All relationships investigated in this research are set out in Table 2, resulting in the generation of 92 regression models.

$$Y = a + b \bullet X \quad [Linear – Lin] \tag{1}$$

$$Y = a \bullet e^{b \bullet X} \quad [Exponential – Exp] \tag{2}$$

$$Y = a + b \bullet ln(X) \quad [Logarithmic – Log] \tag{3}$$

$$Y = a \bullet X^b \quad [Geometric – Geo] \tag{4}$$

The relations tested were evaluated *via* an analysis of variance (ANOVA) of the regression models, considered at a 5% significance level (α). Insignificance of the tested models was assumed to be a null hypothesis (H_0: $\beta = 0$) and representativeness as an alternative hypothesis (H_1: $\beta \neq 0$). P-values higher than the significance level considered implies accepting H_0 (the model tested is not representative, X variations are unable to explain the variations in Y), refuting it otherwise (the tested model is representative), as pointed out by Montgomery (2005).

In addition to using an ANOVA, which allows for choice in the acceptance of the representation of the tested models, the values of coefficient of determination (R^2) were obtained to assess the ability of the independent variable's fluctuation effect to explain the dependent variable. Thus, it became possible to choose from among the models considered significant, and the best fit tested by relationship.

Table 2. Relationship Investigated in this Research

Dependent Variable	Independent Variable	Relation
ρ_{bas}	ρ_{12}	$\rho_{bas} = f(\rho_{12})$
ρ_s	ρ_{12}	$\rho_s = f(\rho_{12})$
β_r	ρ_{bas}; ρ_{12}; ρ_s	$\beta_r = f(\rho_{bas})$; $\beta_r = f(\rho_{12})$; $\beta_r = f(\rho_s)$
β_t	ρ_{bas}; ρ_{12}; ρ_s	$\beta_t = f(\rho_{bas})$; $\beta_t = f(\rho_{12})$; $\beta_t = f(\rho_s)$
β_l	ρ_{bas}; ρ_{12}; ρ_s	$\beta_l = f(\rho_{bas})$; $\beta_l = f(\rho_{12})$; $\beta_l = f(\rho_s)$
β_v	ρ_{bas}; ρ_{12}; ρ_s	$\beta_v = f(\rho_{bas})$; $\beta_v = f(\rho_{12})$; $\beta_v = f(\rho_s)$
CA	ρ_{bas}; ρ_{12}; ρ_s	CA = $f(\rho_{bas})$; CA = $f(\rho_{12})$; CA = $f(\rho_s)$
α_v/PSF	ρ_{bas}; ρ_{12}; ρ_s	$\alpha_v/PSF = f(\rho_{bas})$; $\alpha_v/PSF = f(\rho_{12})$; $\alpha_v/PSF = f(\rho_s)$
β_v/PSF	ρ_{bas}; ρ_{12}; ρ_s	$\beta_v/PSF = f(\rho_{bas})$; $\beta_v/PSF = f(\rho_{12})$; $\beta_v/PSF = f(\rho_s)$

RESULTS AND DISCUSSION

Initially, the decision was not to record individual values of the parameters obtained in the tests performed, given the large volume of digital data. Thus, Figs. 1, 2, and 3 showed graphs summarizing the results for each property.

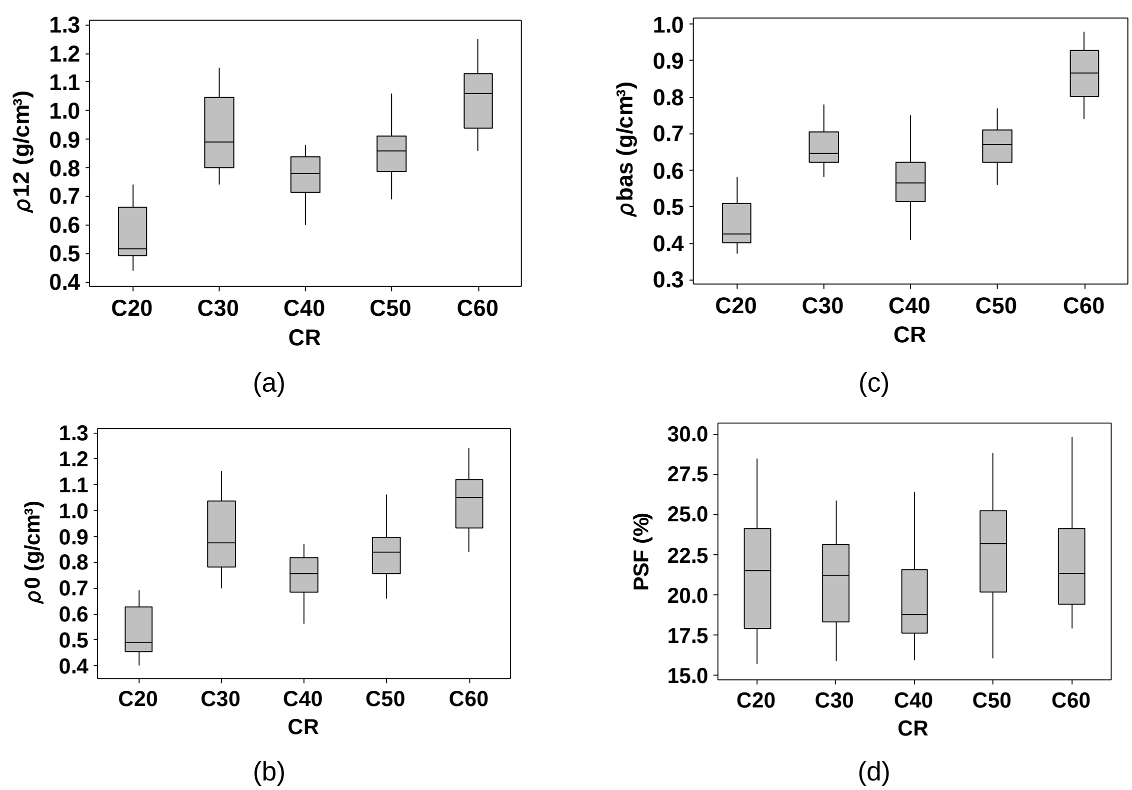

Fig. 1. Boxplots in classes of resistance (CR) for: (a) ρ_{12}, (b) ρ_0, (c) ρ_{bas}, and (d) PSF

The graphs are in the form of boxplots subdivided in classes of resistance, with the mean and percentiles shown for each (0%, 25%, 75%, and 100%).

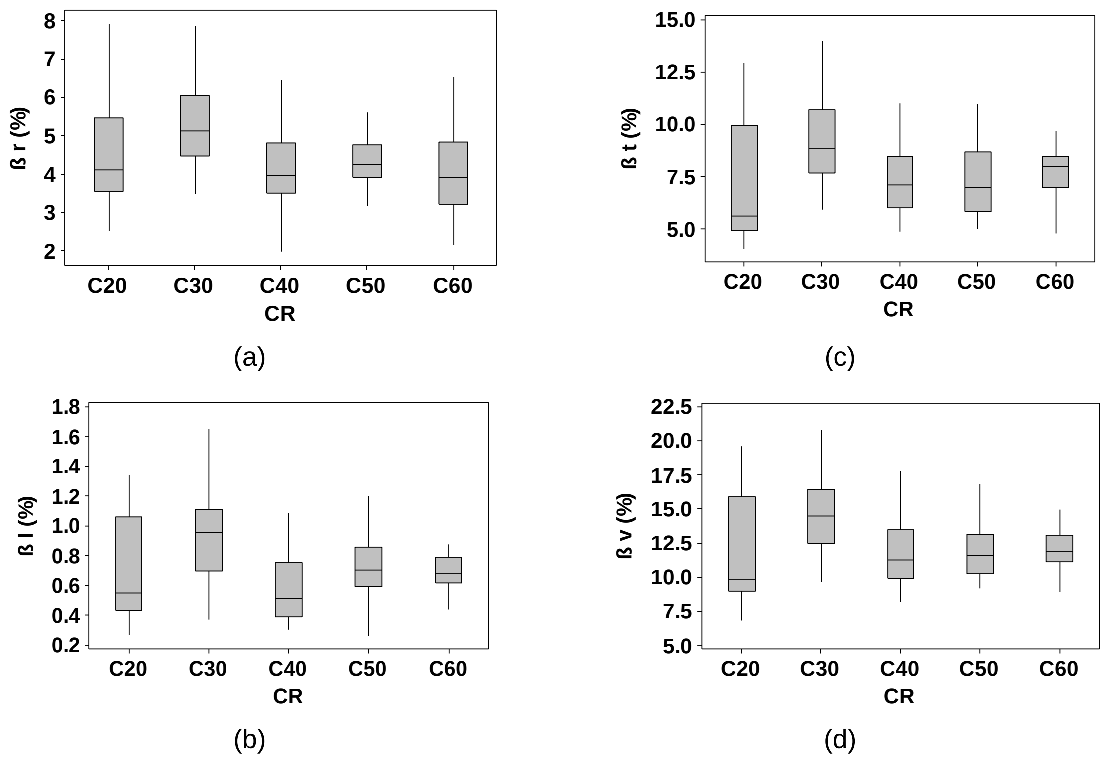

Fig. 2. Boxplots in classes of resistance (CR) for: (a) β_r, (b) β_t, (c) β_l, and (d) β_v

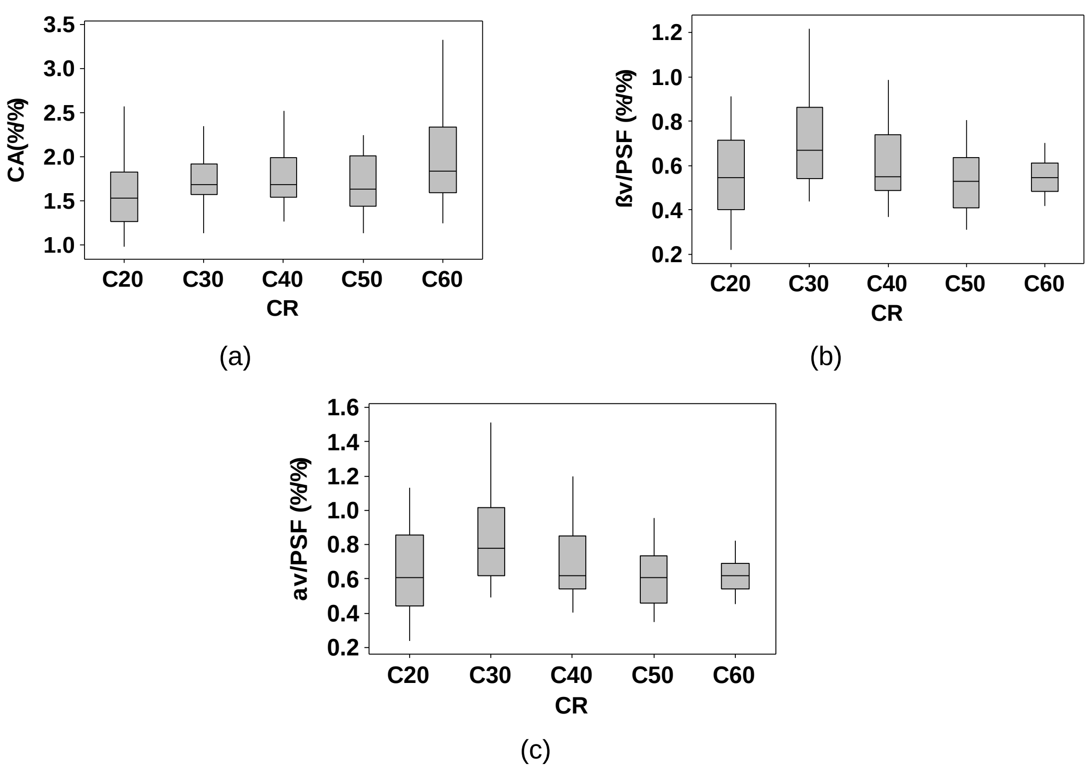

Fig. 3. Boxplots in classes of resistance (CR) for: (a) CA, (b) [β_v/PSF], and (c) [α_v/PSF]

The results contained in Figs. 1 through 3 follow the same trend found in related literature, as presented by Usta and Guray (1998), Logsdon (1999), Boldin *et al.* (2008), Lubas *et al.* (2008), and Quartaroli *et al.* (2010). The strength characteristic value could be non-directly proportional to the density due to variations of anatomical parameters between species. This explains the higher density values found for the C30 class related to the C40 class, as researched by Almeida *et al.* (2016).

Table 3 presents the best fit obtained by the investigation of the relations of different groups (showing the best fit with ρ_{12} as an estimator), determination coefficient (R^2), and P-values of the models, which were all considered significant by ANOVA (P-value < 0.05). No one regression model tested with ρ_s and ρ_{bas} as estimator showed significance.

Table 3. Adjustments of Models for Groups

Relation	Best Fit	P-value	a	b	R^2 (%)
$\rho_{bas} = f(\rho_{12})$	Geo	0.0000	0.7472	0.8366	72.92
$\rho_s = f(\rho_{12})$	Geo	0.0000	0.9855	1.0712	99.69
$\beta_r = f(\rho_{12})$	Log	0.0012	4.6888	1.0669	5.70
$\beta_t = f(\rho_{12})$	Geo	0.0000	8.2556	0.4802	19.58
$\beta_l = f(\rho_{12})$	Geo	0.0003	0.7392	0.4524	7.14
$\beta_v = f(\rho_{12})$	Geo	0.0000	13.164	0.3806	17.01
$CA = f(\rho_{12})$	Geo	0.0001	1.8114	0.2382	6.83
$\alpha_v/PSF = f(\rho_{12})$	Geo	0.0000	0.7099	0.4080	9.57
$\beta_v/PSF = f(\rho_{12})$	Geo	0.0001	0.6136	0.3552	8.68

Table 3 shows that all relations between ρ_{12} were considered significant by an ANOVA test and showed the best quality setting. Values of 72.9% and 99.7% were displayed for the coefficient of determination in the estimation of densities, with ρ_{12} as an estimator of ρ_{bas} and ρ_s in the geometric model, respectively. Figure 4 shows the graphs with the best adjustments in the estimation values of densities.

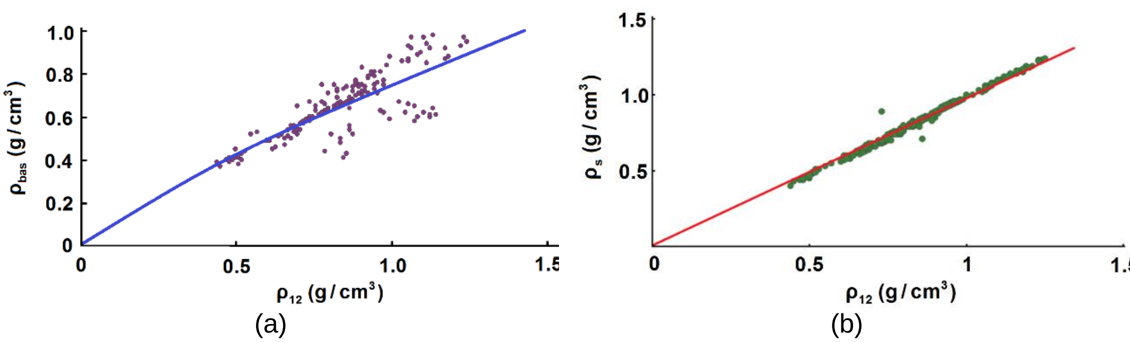

Fig. 4. (a) ρ_{12} as an estimator of ρ_{bas}; and (b) ρ_{12} as an estimator of ρ_s

For ρ_{12} as an estimator of the shrinkages of the studied essences, ρ_{12} as an estimator of β_r was the only setting in which the logarithmic model was the most representative. It can be concluded that the best settings were in the estimation of β_v (R^2 = 17.01%) and β_t (R^2 = 19.58%). Figure 5 shows the graphs with the best settings in the estimation of shrinkages by density.

In rate estimations, the best adjusted value obtained for R^2 was 8.68% for the rate of volumetric shrinkage. Figure 6 contains the graphics with the optimal settings.

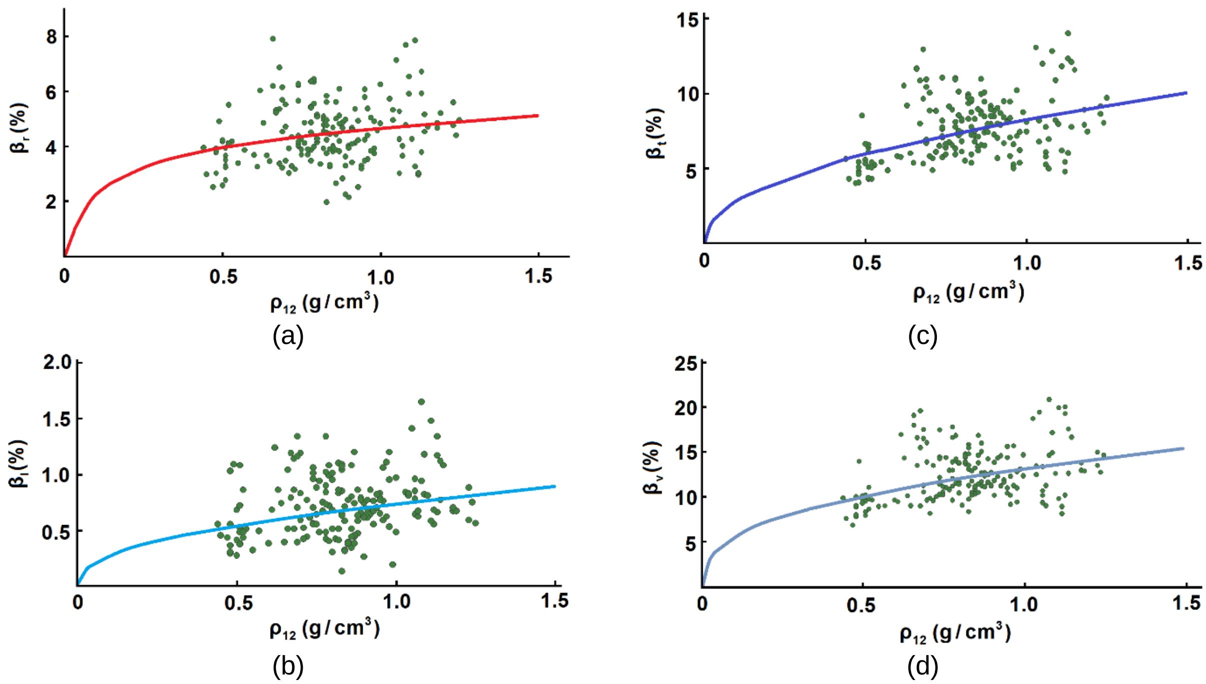

Fig. 5. (a) ρ_{12} as an estimator of β_r; (b) ρ_{12} as an estimator of β_t; (c) ρ_{12} as an estimator of β_l; and (d) ρ_{12} as an estimator of β_v

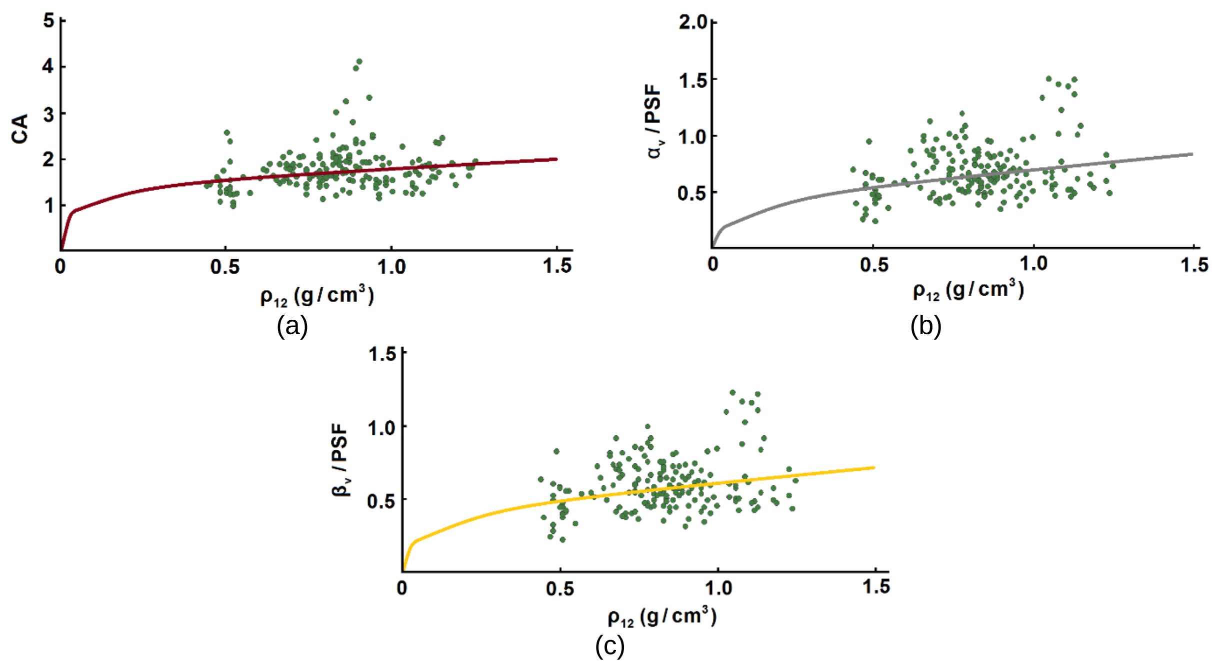

Fig. 6. (a) ρ_{12} as an estimator of CA; (b) ρ_{12} as an estimator of β_v/PSF; and (c) ρ_{12} as estimator of α_v/PSF

Even though the regression models were considered significant by the analysis of variance (P-values<0.05 – Table 3), most of the coefficients of determination were less than 20%, except for the relations $\rho_{bas} = f(\rho_{12})$ (72.92%) and $\rho_s = f(\rho_{12})$ (99.69%), which implies low precision of the models obtained in the cases of interest.

Moreover, density as an estimator of dimensional stability parameters showed great dispersion, as evidenced by the lower values obtained from the determination coefficients (R^2). Anatomical characteristics of Brazilian tropical wood species should be studied, similarly to Toong *et al.* (2014). This cited work considered the anatomical characteristics and mechanical and physical properties of the 50 commercial wood species from Malaysia, which were divided into heavy, medium and light hardwoods according their densities. Linear correlations and multiple regression equations proposed between wood properties and anatomical characteristics were realized by these authors; for all species, correlations between density and fiber thickness index presented Pearson-correlation equal to 0.619. However, tangential and radial shrinkages presented non-significant Pearson-correlation with elements number per square millimeter. For multiple regression equation models to heavy hardwoods, radial shrinkage was estimated with fiber thickness index as parameter and showed adjusted coefficient of determination (R^2Adj) of 0.898. To medium and light hardwoods, the density presented R^2Adj values of 0.993 and 0.980, respectively.

The proposed regression models in this paper are important to support to other studies concerned with correlation among anatomical characteristics and properties of Brazilian tropical wood species, especially from Amazon Forest, where Steege *et al*. (2016) have estimated that there are approximately 16,000 tree species.

CONCLUSIONS

1. Number of species used and the sampling based on classes of resistance (according to NBR7190 1997) did show the appropriate representation of the results achieved.
2. The best adjustments reached in this study refer to density as an estimator of the basic and anhydrous densities, which was evidenced by the values obtained for the coefficient of determination.
3. In the case of density as an estimator of dimensional stability parameters, the highest value reached was R^2 = 19.58%, which illustrated that the density could be a bad indicator of the dimensional stability of Brazilian tropical woods.

ACKNOWLEDGMENTS

The authors are grateful for the support of: CNPq (National Council for Scientific and Technological Development) of the process 130601/2014-4, LaMEM (Wood and Timber Structures Laboratory) from Department of Structural Engineering (SET) of São Carlos Engineering School (EESC) of University of São Paulo (USP), for providing the facilities and inputs required for this study.

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Article submitted: March 19, 2017; Peer review completed: June 1, 2017; Revised version received and accepted: July 19, 2017; Published: July 25, 2017.
DOI: 10.15376/biores.12.3.6579-6590